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Effects of Counterface Roughness and Conformity on the Tribological Performance of Crosslinked and Non-crosslinked Medical-Grade Ultra-High Molecular Weight Polyethylene

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ABSTRACT

The tribological behavior of crosslinked ultra-high molecular weight polyethylene (UHMWPE) was compared to that of non-crosslinked UHMWPE, used as control sample. A reciprocating pin-on-disk tribometer was used to determine the effects of countersurface roughness and conformity on wear mechanisms occurring during the initial stage of sliding. Pin samples of two different radii of curvature were slid against medical-grade Co-Cr alloy disks with surface roughness ranging from 0.005 to 0.04 μm in a lubricant of bovine serum. Normal loads were chosen to provide physiological contact stresses. The focus of this study was on the dependence of early wear mechanisms on surface roughness and conformity. Although a correlation between coefficient of friction data and dominant wear mechanisms was not observed, different wear mechanisms were found between control and crosslinked UHMWPE. The results of this study provide insight into the differences of the initial wear behavior of non-crosslinked and crosslinked UHMWPE used in total joint replacements.

INTRODUCTION

Ultra-high molecular weight polyethylene (UHMWPE), articulating against a ceramic or metal counterface, is the prime load-bearing material system in most total joint replacements. While the intrinsic mechanical properties of UHMWPE make this polymer well suited for this purpose, methods to further improve the *in vivo* mechanical behavior of UHMWPE are still under development, the principal objective being to reduce the amount of submicron-sized polymer wear particles generated through joint motion. Accumulation of such fine wear debris elicits a foreign body response leading to osteolysis, and eventually to loosening of the prosthesis necessitating revision surgery. Increasing the wear resistance of the polymer surface is thus a high priority in the area of orthopaedics research, as it can be correlated to an increase of the expected life of total joint replacements.

UHMWPE is a semicrystalline polymer. In its non-crosslinked form it is about 50% crystalline. The amorphous phase is well above its glass transition temperature, rendering the polymer susceptible to chain orientation or texture development under contact sliding conditions. Polymer chains in bulk UHMWPE exhibit random orientation. Chain crosslinking through chemical means or radiation results in decreased crystallinity (~20%) and inhibits polymer chain reorientation near the surface in a direction parallel to the direction of sliding. Since such chain re-arrangement is the precursor to wear in non-crosslinked polyethylene [1,2], restricting polymer chain movement should increase the wear resistance of the polymer surface. Although the surface wear resistance of polyethylene can be improved by treatments inducing crosslinking, studies have shown that other bulk mechanical properties may be degraded, such as fracture toughness [3].

Variations in the wear behavior of crosslinked and non-crosslinked polyethylene may be encountered due to significant microstructural differences. Insight into the micromechanics of crosslinked polyethylene may enhance more accurate prediction of *in vivo* behavior and perhaps also lead to improved treatments of the polymer. While several studies have been devoted to characterizing and comparing the wear rates of UHMWPE in both crosslinked and non-crosslinked conditions, very little is known about the effect of roughness and conformity on the early stage of the wear process. Slight increases in surface roughness of the material articulating against the UHMWPE surface have been found to significantly increase the wear rate [4]. Therefore, the main objective of this study was to investigate the initial wear mechanisms of medical-grade UHMWPE sliding against polished Co-Cr alloy disks in bovine serum under contact pressures typical of knee joints.

EXPERIMENTAL METHODS

Specimens

Two types of UHMWPE microstructures were examined in this study: non-crosslinked UHMWPE obtained from tibial inserts (Smith & Nephew, Memphis, TN) and crosslinked UHMWPE obtained from Durasul™ tibial components (Sulzer Orthopedics, Austin, TX). Crosslinking was performed at ~ 100 kGy of electron beam radiation at a temperature below melt, followed by melt annealing at 150 °C. Ethylene oxide (EtO) gas was used to sterilize both polymer materials used in this study. A total of 15 pins of length 19.1 mm were machined from the tibial components of each material. To study the role of surface conformity in total joint replacements, the ends of seven pins from each group were machined to hemispherical shapes of radius equal to 3.2 mm, and those of the remaining eight pins to radius equal to 7.9 mm. The ends of each pin were then polished with fine polishing cloth to remove gross machining marks.

Flat disks of diameter 63.5 mm and thickness equal to 7.9 mm, machined from F77 Co-Cr alloy (Depuy Orthopaedics, Warsaw, IN), were used as the counterface material. Tests were performed using two surface conditions. The first corresponded to an orthopaedic-grade surface finish, and the second represented a roughened surface, similar to those seen in retrieved Co-Cr femoral components [5]. Four of the seven disks were roughened using 600-grit SiC abrasive paper. This procedure created sharp surface features on the counterface that have been shown to be an important factor contributing to the increase of the wear rate of UHMWPE [6].

For each disk, the average surface roughness with respect to the mean profile line, R_a, and peak surface height above the mean line, R_{peak}, were measured using a DekTak IID mechanical stylus profilometer (Sloan Technology Co., Santa Barbara, CA), equipped with a 12.5-μm radius tip, having a vertical resolution of 0.5 nm. R_{peak} gives statistical information about asperity heights above the zero-height plane. Measurements were obtained over 4 mm scan lengths at ten different locations of each disk surface, where reciprocating sliding with the pins occurred during subsequent wear testing. Mean and standard deviation values of the surface roughness parameters of each disk used in this study are given in Table I. The calculations were based on the assumption that the roughness data followed normal distributions.

Experimental Apparatus and Microscopy

A reciprocating pin-on-disk tribometer was used for wear testing. Previous studies have demonstrated that unidirectional sliding does not yield wear rates for UHMWPE relevant to those expected *in vivo* [7]. In the tribometer used in this study, the direction of sliding was reversed after 90° rotation. The friction force between the pin and disk surfaces was continuously recorded by strain gauges that measured the horizontal deflection of the arm holding the pin. The rotational speed was chosen to produce a maximum linear velocity of 35 mm/s for all specimens. In order to keep the rotational speed constant throughout the study, the stroke length of different tests was varied from 15.7 to 37.68 mm. One sliding cycle corresponded to a total distance of sliding equal to 35 mm. The pin was held stationary above the rotating disk under a constant normal load of 10.29 N. The lubricant used in this study was Hyclone Alpha Calf Fraction serum diluted 1:1 with distilled water and 0.1 wt% sodium azide, resulting in a protein concentration of 23 mg/mL. Sodium azide was added to prevent degradation of the bovine serum. The protein concentration corresponds to levels found in healthy synovial joints [8]. All tests were conducted at room temperature and relative humidity typically in the range of 40%-50%.

Table I. Surface roughness of Co-Cr disk specimens

Disk #	R_a (μm)	R_{peak} (μm)
1	0.028 ± 0.004	0.167 ± 0.099
2	0.029 ± 0.003	0.108 ± 0.028
3	0.042 ± 0.007	0.518 ± 0.128
4	0.031 ± 0.002	0.377 ± 0.079
5	0.005 ± 0.001	0.066 ± 0.027
6	0.031 ± 0.003	0.372 ± 0.044
7	0.007 ± 0.002	0.082 ± 0.042

The apparent mean contact pressure $\bar{p}$ between the pin and the disk surfaces was approximately determined using classical Hertz theory. For hemispherical pin and flat disk specimens, $\bar{p}$ is given by

$$\bar{p} = \frac{1}{\pi}\left(\frac{4E^*}{3R}\right)^{2/3} P^{1/3} \tag{1}$$

where P is the normal load, R is the radius of curvature of the hemispherical end of the pin, and E^* is the effective elastic modulus, given by $E^* = \left[\left(1-\nu_1^2\right)/E_1 + \left(1-\nu_2^2\right)/E_2\right]^{-1}$, where E and ν denote elastic modulus and Poisson's ratio and subscripts 1 and 2 refer to UHMWPE and Co-Cr materials, respectively. Assuming $E_1 = 1$ GPa, $\nu_1 = 0.45$, $E_2 = 210$ GPa, and $\nu_2 = 0.3$, the effective elastic modulus is found to be $E^* = 1.25$ GPa. Based on these values, the apparent mean contact pressure obtained from Eq. (1) for pin radii of 3.2 and 7.9 mm is 44.98 and 24.42 MPa, respectively, which is within the contact stress range of healthy synovial joints [9]. Since the polymer is expected to plastically deform under such pressure values, Eq. (1) yields only an approximate estimate of the apparent mean pressure.

After 2, 6, and 8 h of testing, worn polymer surfaces were observed in an Electroscan E3 environmental scanning electron microscope (ESEM) (FEI Company, Hillsboro, OR) in order to study the evolution of wear. The ESEM is an ideal instrument because UHMWPE can be observed at electron microscope magnification levels without the need to coat the sample surfaces with a conductive layer that may alter the topography during observation.

RESULTS AND DISCUSSION

Coefficient of Friction

Figures 1 and 2 show typical friction coefficient responses for four representative material cases. In all experiments, the coefficient of friction evolved to a steady-state value after a relatively short sliding distance (run-in period), thus allowing for the calculation of an average steady-state value after testing for ~2 h. Mean and standard deviation values for the steady-state coefficient of friction (obtained assuming the data followed normal distributions) are given in Table II for different pin radius (conformity) and counterface roughness. The data do not reveal a conformity effect on friction behavior. However, both polymer materials exhibit lower average steady-state friction coefficients when articulated against a smooth counterface than a rough counterface. Higher friction is expected with rough surfaces due to the greater contributions of asperity deformation and plowing friction mechanisms, although adhesion may decrease due to the reduced real contact area in the presence of a rough surface. However, if the dominant process is surface fatigue, resulting from the differential plastic flow and toughness of crystalline and amorphous phases or non-crosslinked and crosslinked microdomains, then the roughness controls the intensity and number of secondary load (asperity) cycles accumulating in each passage of the pin (primary load cycle). Fewer secondary load cycles are produced with the rougher counterface, though the stress intensity at asperity microcontacts is higher. Thus, cycle-dependent mechanisms, such as surface pitting, could be impeded during articulation against a rougher surface. This may provide explanation for the less surface damage of both crosslinked and control pins articulated against the rougher Co-Cr disk surfaces.

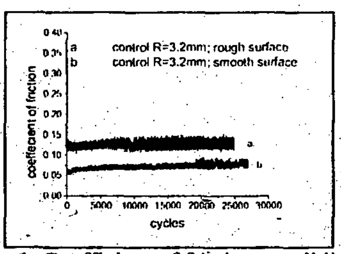


Figure 1. Coefficient of friction vs. sliding cycles for control UHMWPE.

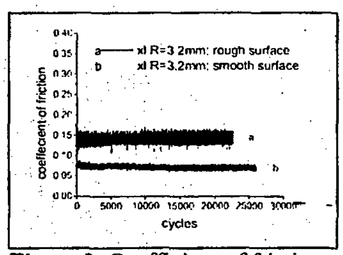


Figure 2. Coefficient of friction vs. sliding cycles for crosslinked UHMWPE.

Table II. Steady-state coefficient of friction vs. Co-Cr counterface roughness

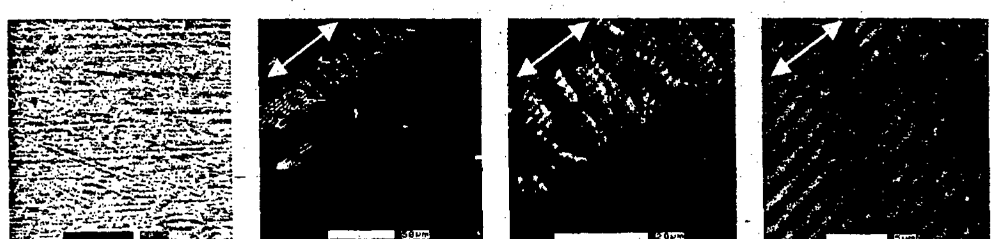
Polymer material	Pin radius (mm)	Smooth counterface	Rough counterface
Control	3.2	0.09 ± 0.02	0.14 ± 0.02
Control	7.9	0.10 ± 0.05	0.16 ± 0.06
Crosslinked	3.2	0.09 ± 0.05	0.19 ± 0.07
Crosslinked	7.9	0.11 ± 0.07	0.17 ± 0.05

Wear Mechanisms

To study the evolution of wear during the initial stage of sliding, the pin surfaces were examined after 2, 6, and 8 h of testing, corresponding to approximately 6,200, 18,500 and 24,700 sliding cycles. After 2 and 6 h of continuous sliding, the original machining and polishing marks (e.g., see Figs. 3(a) and 4(a)) were still visible, regardless of the counterface against which the pin was tested, for both crosslinked and control materials. After 8 h of testing, the surfaces of the control and crosslinked pins with radius of curvature equal to 7.9 mm did not reveal any discernible changes; however, the surface topographies of the pins with the lower conformity exhibited noticeable differences. Control pins tested against the smooth counterface revealed surface features similar to those observed by Rostoker et al. [2]. That study showed regions of plastic deformation with a striated topography, similar to those shown in Figs. 3(b)-3(d). Surface features observed in the present study, such as folding and rippling, could contribute to adhesive wear by creating regions more susceptible to rupture than the bulk material. The produced particles could then lead to third-body abrasive wear, thereby accelerating surface deterioration.

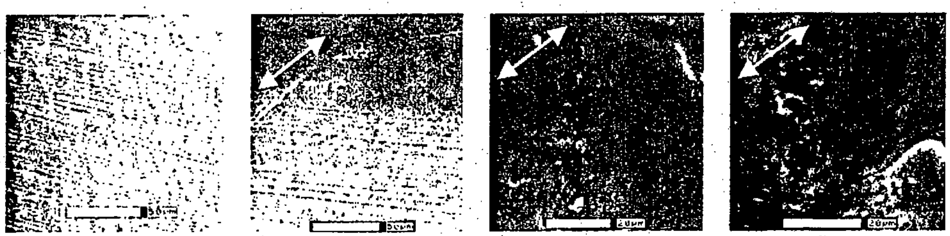
Crosslinked pins tested against the same smooth counterface showed pitting similar to that observed in crosslinked retrievals [10]. Surface pitting can be considered to be a manifestation of adhesion and surface rupture due to excessive localized plastic shearing. As discussed above, the roughness of the counterface may promote this wear mechanism. It is hypothesized that wear of the amorphous phase of UHMWPE occurs at a rate higher than that of the crystalline phase, leading to a surface consisting of protruding harder microdomains. These low-toughness surface features presumably undergo microfracture during repeated asperity sliding, leading to the surface topographies shown in Figs. 4(b)-4(d).

Neither material showed significant surface evolution against the rougher counterface. It is thought that the rougher counterface actually enhanced lubrication by providing serum paths at the contact region, thereby resulting in less wear in the early stages of sliding.



(a) (b) (c) (d)

Figure 3. Representative ESEM micrographs of control UHMWPE surfaces obtained (a) before and (b)-(d) (representing three different magnifications) after testing for 21,300 sliding cycles against a smooth Co-Cr counterface. (Arrows denote direction of sliding.)



(a) (b) (c) (d)

Figure 4. Representative ESEM micrographs of crosslinked UHMWPE surfaces obtained (a) before and after testing for (b) 27,000 (c) 26,200 and (d) 18,400 sliding cycles. (Sliding occurred against (b) smooth and (c), (d) rough Co-Cr counterfaces. Arrows denote direction of sliding.)

CONCLUSIONS

Surface damage of non-crosslinked and crosslinked UHMWPE was investigated in this study. Distinct differences in surface damage modes were observed between crosslinked and non-crosslinked polymers after continuous reciprocating sliding against orthopaedic-grade Co-Cr alloy surfaces immersed in alpha calf fraction serum. Surface rippling and folding were the dominant surface deformation features on the non-crosslinked material, while crosslinked UHMWPE showed evidence of pitting and cracking. The latter behavior may be attributed to the reduced modes of plasticity of the crosslinked material. Despite the lower wear rate of the crosslinked material (afforded by the resistance to orientation softening), crosslinking may yield damage modes not possible with untreated polyethylene. Differences in plasticity between adjacent crosslinked and non-crosslinked regions may promote localized excessive shearing, leading to micropitting due to the high shear strain gradients at the boundaries of different microdomains. This highlights the need for further investigation of wear mechanisms commencing at the micro- and nano-scale. Therefore, in addition to the wear rates of different types of UHMWPE used in total joint replacements, it is essential to obtain insight into the different modes of plasticity and wear micromechanisms encountered during the early stage of sliding, and to further examine the precursors of the steady-state wear process.

REFERENCES

[1] C. Klapperich, K. Komvopoulos, L. Pruitt, J. Tribology **121**, 394-402 (1999).
[2] W. Rostoker, E. Y. S. Chao, J. O. Galante, J. Biomed. Mater. Res. **3**, 317-335 (1978).
[3] D. A. Baker, R. S. Hastings, L. A. Pruitt, J. Biomed. Mater. Res. **4**, 573-81 (1999).
[4] P. S. Barbour, M. H. Stone, J. Fisher, Proc. Inst. Mech. Eng., Part H, **6**, 569-76 (2000).
[5] A. P. Elfick, S. L. Smith, A. Unsworth, J. Arthroplasty **7**, 901-8 (2000).
[6] P. S. Barbour, M. H. Stone, J. Fisher, Proc. Inst. Mech. Eng., Part H, **6**, 569-76 (2000).
[7] C. R. Bragdon, D. O. O'Connor, J. D. Lowenstein, M. Jasty, W. D. Syniuta, Proc. Inst. Mech. Eng., Part H, **3**, 157-65 (1996).
[8] H. Saari, S. Santavirta, D. Nordstrom, P. Paavolainen, Y. T. Konttinen, J. Rheumatol. **1**, 87-90 (1993).
[9] D. L. Bartel, V. L. Bicknell, T. M. Wright, J. Bone Joint Surg. (Amer.) **7**, 1041-51 (1986).
[10] S. Greenwald, Annual Meeting Amer. Assoc. Orthop. Surg., 13-17 Feb. 2002, Dallas, TX.